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REPORT NO. MT-037
NOVEMBER 1975

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EXPLOSIVE COMPACTION OF POWDERED METALS, PHASE I

A PROJECT OF THE
MANUFACTURING TECHNOLOGY PROGRAM
NAVAL SEA SYSTEMS COMMAND

FINAL REPORT



NAVAL ORDNANCE STATION
LOUISVILLE, KENTUCKY 40214

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ABSTRACT

This is the final project report on a study to determine the feasibility of explosively compacting powdered metals to form missile and other ordnance parts. The work was conducted at the Naval Ordnance Station, Louisville, Kentucky. At the outset of this project, it was believed that with the ability to generate extremely high pressure with explosives, one could achieve close to 100% theoretical density by using explosives to compact metal powders. During the course of the project, densities as high as 97.9% of theoretical were attained with powdered steel compacts. However, considerable precompaction preparation was necessary to achieve this. The most difficult problem encountered was driving off oxides in the steel powder. This was never satisfactorily accomplished even with preheating the powder samples in a vacuum prior to compaction. Sintering in a reducing atmosphere was also tried without success. It became more evident as the project progressed that the cost of achieving acceptable physical properties would be very high and make explosively compacting parts infeasible.

In addition to the above study, a shelter was built for a 16 inch gun barrel breech section converted to a dual mode (vacuum chamber and isostatic press) pressure chamber system. The system was installed and testing in the vacuum mode was started. Part of the breech plug assembly failed during the tests and a replacement part was not received until after the project funds expired. After the failure of the breech plug, the chamber was converted to the isostatic press mode. The chamber will be used in this mode for compacting powdered metal using the wet bag process.

FOREWORD

This is the final report of work completed under NAVORDSYSCOM Work Request WR-3-5960 issued to investigate the feasibility of using explosive force to form missile and ordnance parts from powder metal. The study was performed by the Naval Ordnance Station, Louisville, Kentucky.

Funding was provided by the Industrial Resources and Facilities Division (ORD-047) of NAVORDSYSCOM under the Manufacturing Technology Program (MTP) and the project was completed for the Naval Sea Systems Command (SEA-070). Funding was also received to build a shelter for a dual purpose pressure chamber manufactured from a 16 inch gun barrel breech section under a previous MTP project.

Acknowledgment is given to the following persons for their generous contributions of time and knowledge:

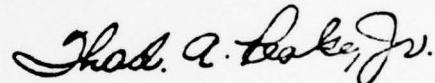
Kenneth H. Moyer

Manager, Special Alloys
Hoeganaes Corp.
Riverton, New Jersey

Robert H. Wittman

Metallurgy Division
Denver Research Institute
Denver, Colorado

"This Manufacturing Technology report has been reviewed and is approved."



THAD PEAKE
Director, Manufacturing
Technology Department
Naval Ordnance Station
Louisville, Kentucky

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SECTION I
INTRODUCTION

In the ordnance field there are parts which are made to close tolerances, must be strong and reliable, and are only used once. A good example is the launcher shoes on a missile. Because of the strength and reliability requirements, such a part is often machined from a forging and there is quite a bit of waste in the form of chips.

The original idea behind this project was that through the use of powder metallurgy, the cost of items such as bomb lugs and the shoes which connect a missile to a launcher could be reduced due to a reduction of machining and waste material. In order to achieve densities necessary for sufficient strength, explosive force was to be used. To a certain extent, the strength of a powdered metal part is directly related to the density of the part. It was thought that densities approaching 100% of theoretical could be achieved with the high pressures which can be generated with explosives.

SECTION II
FAMILIARIZATION

At the start of the project, it was necessary to become acquainted with conventional powdered metal processing, determine what types and alloys were available, and the "state of the art" as far as explosive compaction was concerned. Published information on explosive compaction was studied during the proposal stage of the project; however, there is little available. Fortunately, there were people in the high velocity metalworking field who were willing to discuss their experience in this area. Advice on compaction techniques was received from Mr. Albert Doherty of Electroform, Inc., of Fort Worth, Texas, and Mr. Robert Wittman of the Denver Research Institute, University of Denver, Denver, Colorado.

NOSL personnel visited the Hoeganaes Corporation plant in Riverton, New Jersey, and discussed this project with Mr. Kenneth Moyer who is an internationally recognized authority in the powder metallurgy field and proved to be a valuable contact during the course of the project. Mr. Moyer had also had some experience with explosive compaction of powdered metals. All of the people consulted agreed that one major problem was eliminating radial cracks which propagate from the center of a compact (such as the longitudinal axis of a cylinder) outward. This type of cracking is caused by a reflection of shock waves as they meet at a central point. The shock waves are generated by the compacting explosive charge and must be attenuated or dissipated to eliminate cracking. Several techniques, which will be discussed later, were suggested.

Finally, one engineer attended the International Conference on Powder Metallurgy held in Toronto, Canada, in July 1973. The majority of the presentations were on conventional powder metallurgy. One paper was given on high energy compaction by a Russian scientist. However, the content was very limited and little gain was realized from listening to him.

SECTION III

COMPACTION TRIALS

Explosive compaction attempts were started with the intent to develop a satisfactory technique for compacting powders at ambient temperature and without the inclusion of shock absorbing inserts. As stated previously, one of the major problems in explosive compaction is cracking due to reflected shock waves. Two methods of solving this problem are: one, to compact powders in a semi-molten state; and, two, use dissipating cores. Neither approach was considered applicable to the production of high strength missile and ordnance components. The factors involved in the development of an ambient temperature compaction technique were: powder preparation, powder containerization, explosive detonation characteristics, and means of applying explosion pressure to powder.

The precompaction preparation of the powder became increasingly important as the project progressed. A 100 lb sample of Hoeganaes Ancorsteel 4600 was obtained for the development program. The alloy was described by Hoeganaes as a modified AISI 4600 with a high hardenability. The alloy seemed to be applicable to the manufacture of ordnance components. The powder, as received, contained approximately 400 parts per million (ppm) attached oxygen which had to be eliminated. Since there was no carbon in the powder as received, it was also necessary to add carbon in the form of graphite. The graphite acted as a lubricant, a carbon source for hardenability, and a carbon source to combine with the attached oxygen during the sintering of the metal after compaction. After the powder was mixed with graphite, it had to be put in some sort of container.

The first compaction trials were directed towards producing solid cylinders which could be used as samples for physical and chemical analyses. The first containers were made of thin walled aluminum tubing swaged over grooved plugs at either end.

As work progressed, it was discovered that the attached oxygen could not be satisfactorily driven off during sintering so it was necessary to heat the powder-graphite mixture prior to the compaction. As a result, it was necessary to use stainless steel containers in order to avoid contaminating the powder during the preheat. The containers were made of thin-wall tubing with end plugs pressed into each end.

In addition to the chemical aspects of preparing the powder for compaction, it was necessary to take steps to allow for the mechanics of compaction. The powdered metal in the as-received condition has an apparent density. The object of compacting the powder is to achieve a densification approaching 100% of theoretical. It was found that the best explosive compaction results were obtained when the powdered metal was prepressed. The prepressing was accomplished by over filling the tubular container and then pressing the end plug into the tube. While the pressure was being applied, the sample was tapped vigorously in order to insure uniform densification. After the samples were prepressed, they were soaked in a vacuum furnace in order to drive off the attached oxygen on the powdered metal. The samples were then explosively compacted.

Several techniques were used for the compaction. The most successful technique was a stand-off type done underwater. The powder container was mounted on a plate and a low velocity sheet explosive was placed inside a mailing tube and mounted on the same plate (Figure 1) such that the mailing tube and powder container were concentric. With the explosive charge located in this manner, there was about a one inch radial gap between the explosive charge and the workpiece. The assembly was then immersed in water and the explosive detonated. The explosive force was transferred to the powder canister through the water which filled the gap. The water transfer media tends to lengthen the pressure impulse time, thereby producing more of a "squeezing" action than the pressure generated by a charge directly in contact with the powder container. It was discovered that the powder was very sensitive to shock and it was necessary to position detonators and initiating charges away from the main body of the powder charge. It was also observed that undesirable effects were created by initiating the compacting charge at one end. As the detonation front progressed towards the opposite end of the charge, there was a longitudinal component of the force exerted on the powdered metal which induced a stretching action on the compact. This resulted in the formation of the transverse cracks in the compact. Under the circumstances, there was little that could be done. The use of longitudinal strips of high velocity explosive would cause the explosion of the main charge to be more implosive but the brisance of the initiating strips would damage the compact.

Five compaction trials were conducted on the Ancorsteel 4600. Detailed test data are contained in Appendix A. The highest density achieved was 97.99% of theoretical. All compacts were checked for density, carbon content, and evidence of attached oxygen. Charpy impact samples were taken from compact no. 4. The impact test results were 10 ft-lbs, 8 ft-lbs, and 10 ft-lbs which were brittle failures. Further inspection revealed the presence of attached oxygen within the compact.

The problem of eliminating the attached oxygen became the major stumbling block in this project. It was not considered advisable to develop techniques for compacting complicated shapes unless cylindrical samples with acceptable physical properties could be obtained. With iron oxides present in the compact grain boundaries, this was not possible. After discussing the problem with Mr. Kenneth Moyer of Hoeganaes, Inc., it was obvious that if the oxygen was not eliminated prior to the explosive compaction, it could not be eliminated during sintering or subsequent heat treatment. The only solution to the attached oxygen problem was to preheat the powdered metal in a vacuum prior to compaction. The equipment and labor required to prevent recontamination of the powder made it economically unfeasible to use explosively compacted powdered metal parts in order to replace machined forgings.

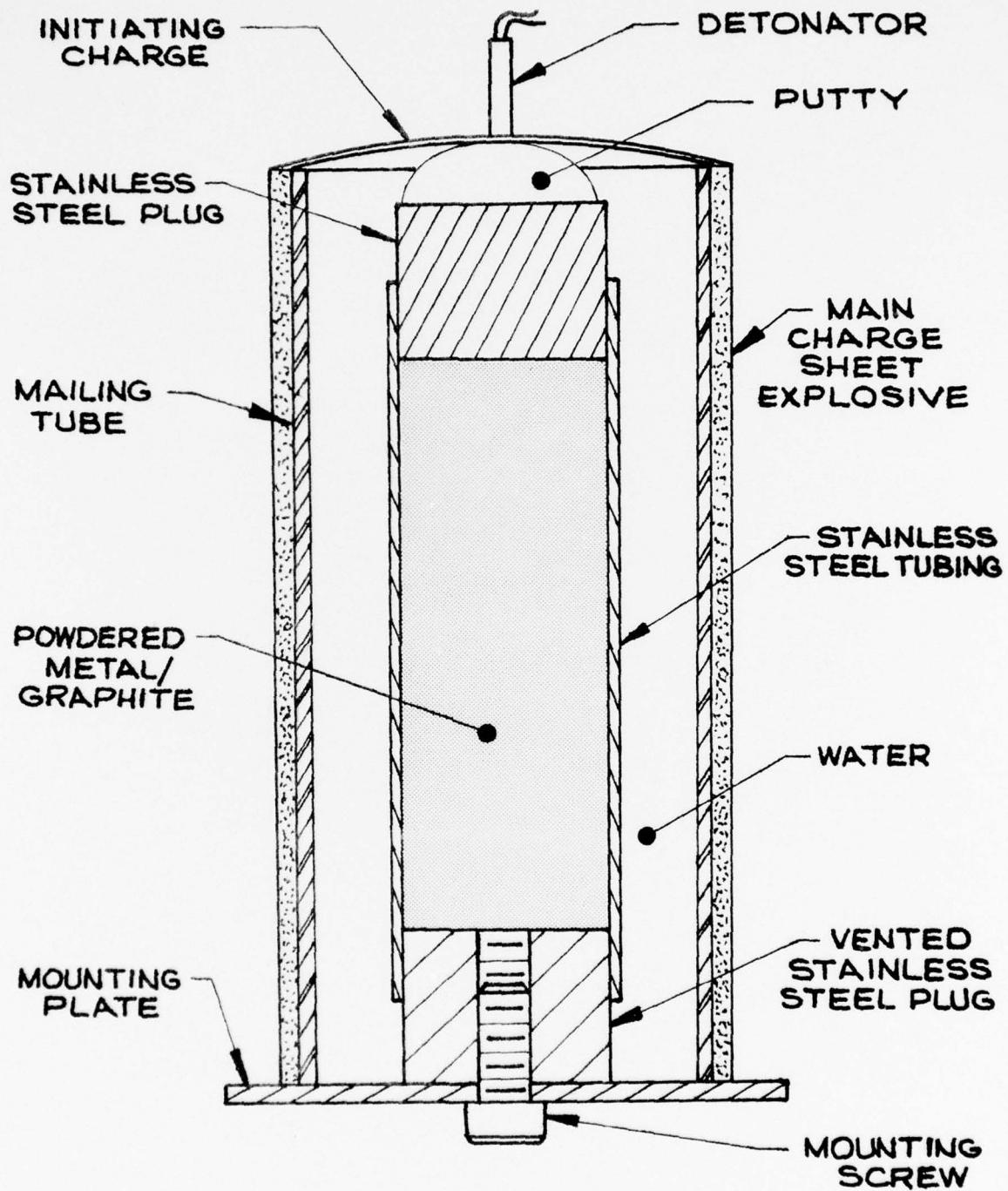


FIGURE 1

COMPACTI ON SET-UP

SECTION IV
DUAL PURPOSE CHAMBER

A prefabricated steel building was erected as a shelter for the dual purpose chamber system. The system was installed with all the necessary utilities, i.e., city water, electricity, natural gas and compressed air (Figures 2 - 5).

After the combination vacuum-isostatic press system had been installed, it was necessary to establish the maximum amount of explosive that could safely be detonated in the chamber in the vacuum mode. The chamber O.D. was strain gaged in order to measure hoop and longitudinal stresses on the chamber O.D. and hoop stress on the plugged end of the chamber. The firing tests were started with a 1/2 pound block of TNT. The second shot was 1 pound of TNT. At this point, the central component of the breech plug, called the mushroom, failed at its outer end where it was fastened to the breech mechanism. The stresses measured at the three points were used to calculate the internal pressure for each shot. For the half pound shot, the pressure was 47,012 psi and for the pound, 68,000 psi. One of the problems encountered during the tests was the generation of a tremendous amount of soot. An explosive contains an oxidizing agent as part of its chemistry. However, since the test detonations occurred in a vacuum, it was evident that either an explosive with excessive oxidant would have to be used for all chamber work, or an additional scavenging system would be required to dispose of the soot and other detonation by-products. Up to the time of this writing, it has not been possible to use the chamber in the vacuum-explosive forming mode.

After the vacuum mode tests were stopped, the chamber was converted over to the isostatic press mode. Considerable time was spent getting the chamber to seal properly. The shock of the detonations from the previous tests had apparently dislocated the seal assembly. It was necessary to remove the entire chamber plug and seal assembly and clean the seal seats before the chamber could be satisfactorily operated in the isostatic press mode.

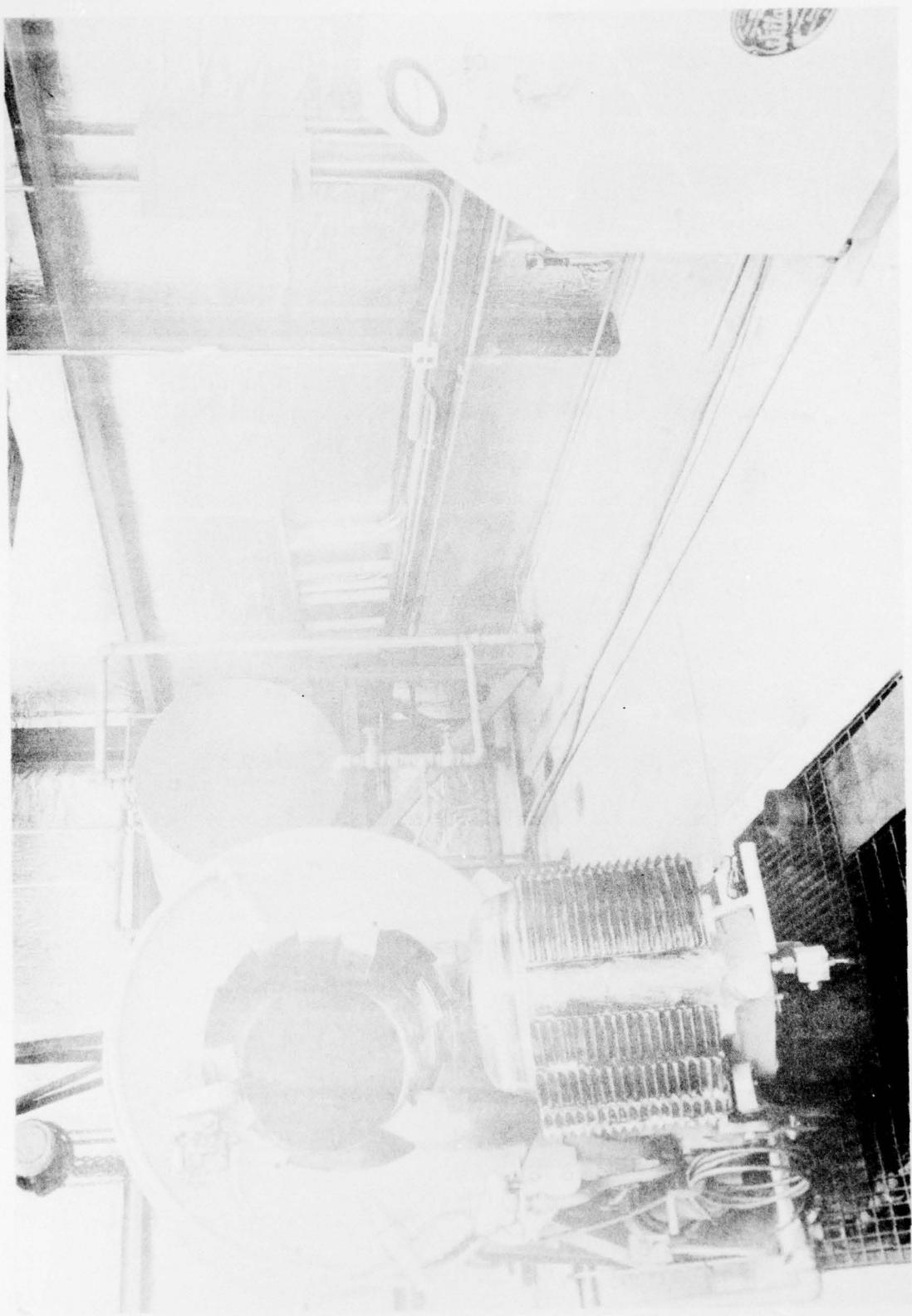
Several attempts have been made to compact powdered metals using the "wet bag" technique. The method gets its name from the fact that the powdered metal is contained in a flexible rubber container. The outer surface of the container (bag) is exposed to the water pressure, hence "wet bag". The degree of densification has been estimated at about 70 to 80 percent of theoretical for the various attempts. It will be necessary to make several rubber bags - plastic bottles were used previously - and use properly prepared metal powder before a true assessment of the isostatic press mode performance can be made.

FIGURE 2
PREFABRICATED BUILDING



CHAMBER AND WATER HOLDING TANK

FIGURE 3



CONTROL PANEL

FIGURE 4

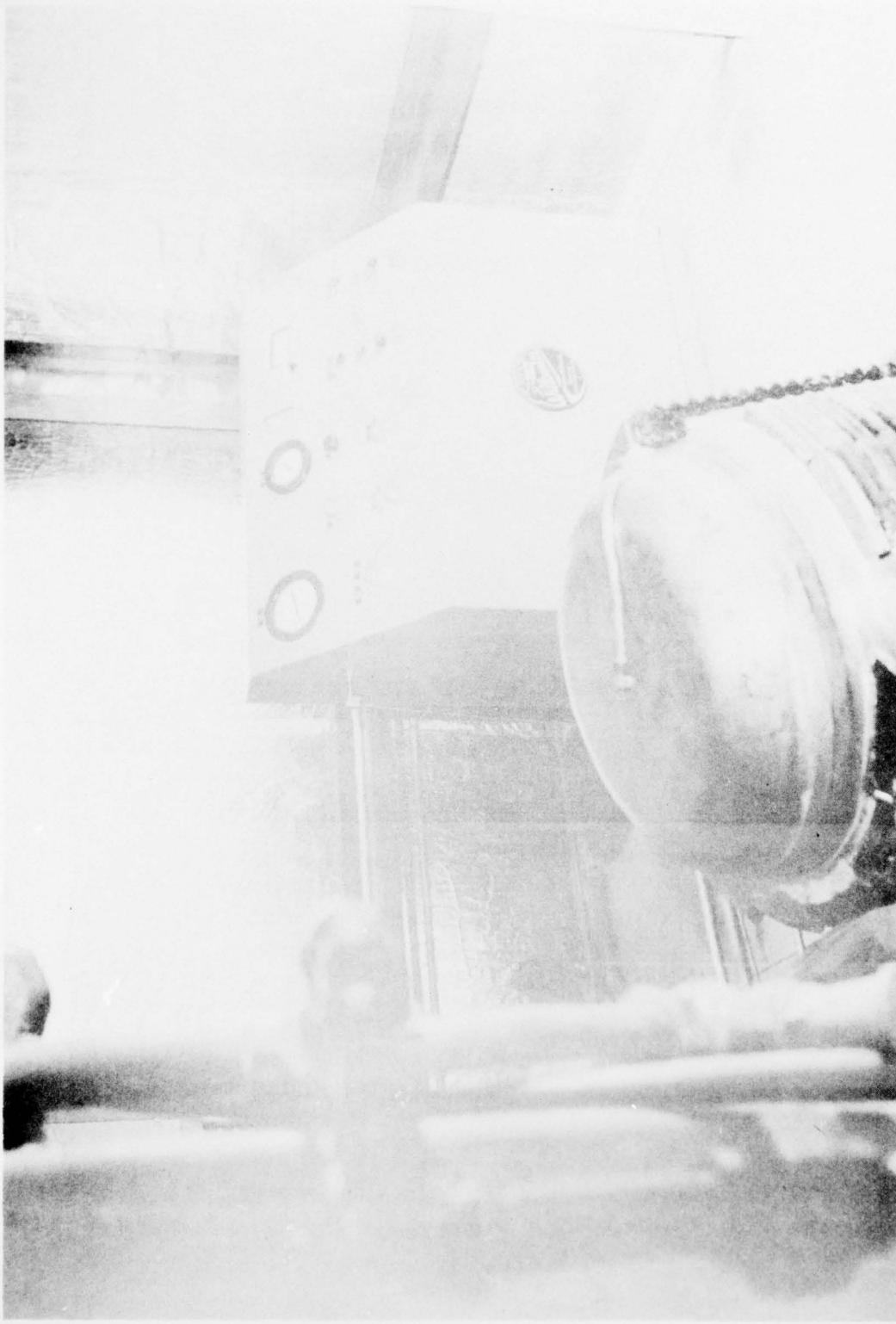
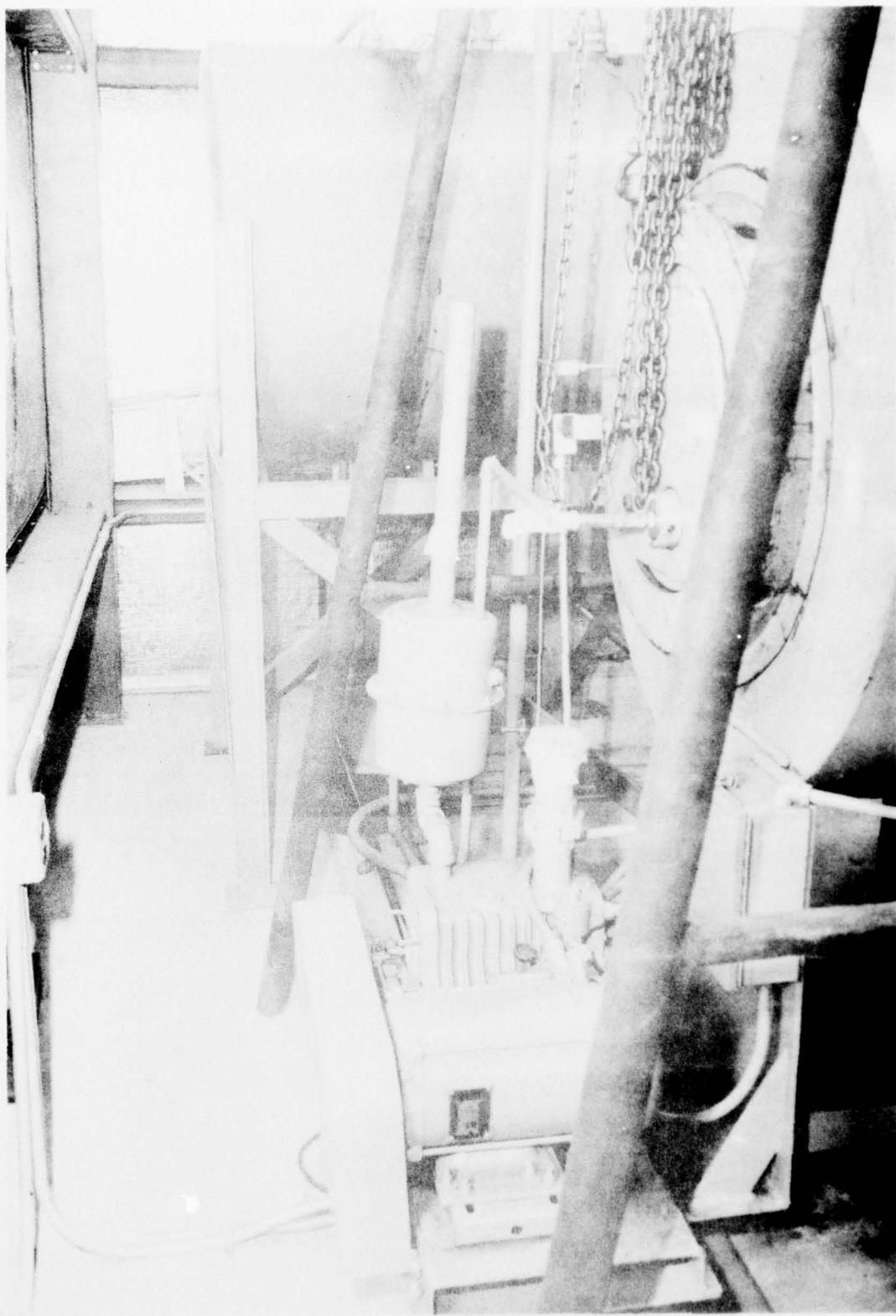


FIGURE 5 VACUUM PUMP MOUNTED ON BACK OF CHAMBER



SECTION V
CONCLUSIONS

The results of the project indicate that it is not feasible to make ordnance components from powdered metal using pressure created by explosive detonation. Explosive compaction of powdered metals is not precisely controllable. Therefore, any parts made in this manner would have to start out with enough machining stock on them to account for variations from part to part. There would then be no advantage over forgings.

The dual purpose pressure chamber will require additional testing in both modes before its full capability can be realized.

SECTION VI
RECOMMENDATIONS

The pressure testing of the dual purpose chamber in the vacuum explosive mode should continue until the maximum explosive charge limit is determined and a solution to the excessive soot problem has been found. In addition, further investigation should be made with intention of developing a capability of producing powdered metal parts using the chamber in the isostatic press mode.

APPENDIX

APPENDIX
EXPLOSIVE COMPACTION DATA

Shot No.: 1

Powder Container: Aluminum tube 1.5 in. I.D. x .030 in. wall with aluminum plugs crimped into each end.

Metal Powder: 450 grams Hoeganaes Ancorsteel 4600 V with 3 percent by weight Southern Graphite No. 1615 graphite.

Explosive Charge: 450 grams Thiokol Sheet Explosive No. 1005 initiated by four equally spaced longitudinal strips of Detasheet.

Compaction Technique: The powder container was mounted on a plate concentric with a cardboard mailing tube such that there was a 1 inch radial clearance between the container O.D. and mailing tube I.D. The sheet explosive was attached to the I.D. of the mailing tube and four longitudinal strips of Detasheet explosive were placed at 90 degree intervals. The assembly was then submerged in water and the explosive charge detonated.

Sintering: One half hour heat-up to 2100°F. Soak at 2100°F for one hour in Endogas reducing atmosphere.

Post Sintering Carbon Content: 1.77%

Comments: After compaction, the green compact had a longitudinal void in the center caused by shock waves reflected at the center of the compact. There were also four longitudinal strips where the powder was adversely affected by the strips of Detasheet. The Detasheet is a high velocity explosive and has a high brisance (shattering effect). Extremely high porosity was caused in the compact during sintering. The porosity was caused by a drastic heat-up and the resulting expansion of gases generated by the sintering.

Further analysis was not conducted due to the quality of the compact.

Shot No.: 2

Powder Container: Aluminum tube 1.5 in. I.D. x .030 in. wall with aluminum plugs crimped into each end.

Metal Powder: 471 grams of Ancorsteel 4600 V with 1 percent by weight No. 1615 graphite.

Explosive Charge: 460 grams Thiokol No. 1005 sheet explosive initiated with a disk of Detasheet at one end.

Compaction Technique: The powder container was mounted on a plate concentric with a cardboard mailing tube such that there was a 1 inch radial clearance between the container O.D. and the mailing tube I.D. The sheet explosive was attached to the mailing tube I.D. and a Detasheet disk was placed over the top of the assembly like a cap. The assembly was then submerged in water and the explosive detonated.

Green Density: 94.5% of theoretical

Sintering: Heat-up was started at 300°F. The sample was heated to 2000°F taking 2 hours and held at 2000°F for 1.5 hours. The sample was allowed to cool to 300°F taking 2 hrs. The sample was in an Endogas atmosphere during the total sintering cycle.

Post Sintering Carbon Content: The sample had a carbon rich zone and a low carbon zone. The contents were .18 percent and .09 percent respectively.

Comments: A specimen of the sintered compact was mounted and etched with a 5 percent Nital solution. The etched specimen had zones of greatly differing carbon content. The O.D. and center areas had low carbon with a higher concentration in between.

Attempts were made to perform chemical analyses on both the green and sintered compacts. However, the samples were not sufficiently homogeneous to get consistent readings without first melting the samples in argon. The chemical analysis was as follows:

C	S	Si	Mn	Cr	Mo	Ni
.14	.028	0	.32	0	.37	1.66

Shot No.: 3

Powder Container: 302 Stainless Steel tube 2.00 in. I.D. x .050 walls with stainless steel end plugs pressed and crimped into each end.

Metal Powder: 1100 grams Hoeganaes Ancorsteel 4600 V plus .25 percent No. 1615 graphite.

Explosive Charge: 1440 grams Thiokol No. 1005 sheet explosive initiated with a disk of Detasheet.

Compaction Technique: The powdered steel-graphite was pressed into the container using 5 tons maximum loading. The canister was plugged with a stainless steel end plug which had a threaded hole in it. The assembly was then soaked for 3 hours at 1650°F in a vacuum furnace. It was then cooled to 400°F with Nitrogen and allowed to furnace cool until it could be handled. The hole in the end plug was plugged with a machine screw as soon as the vacuum furnace was opened. The sample was explosively compacted in the same fashion as the previous samples.

Sintering: The part was heated in a vacuum to 2050°F, held at 2050°F for half an hour, cooled to 400°F with Nitrogen and allowed to furnace cool.

Post Sintering Carbon Content: .20%

Surface Hardness: R_b 90

Density: 97.9% of theoretical

Comments: After compaction the stainless steel canister was removed from the compact. The compact was machined to a cylindrical shape and disks were cut from it for density determination and metallographic analysis. There were transverse cracks in the compact caused by a lack of ductility in the powdered metal compact and the longitudinal stretching action of the longitudinal component of the compacting force.

Shot No.: 4

Powder Container: 304 stainless steel seamless tubing 1.934 in. I.D. x .037 wall with stainless steel end plugs pressed into each end.

Metal Powder: 1439 grams Hoeganaes Ancorsteel 4600 plus .3% by weight No. 1615 graphite.

Explosive Charge: 1180 grams Thiokol No. 1004 sheet explosive initiated with a disk of Detasheet.

Compaction Technique: The powdered steel-graphite was pressed into the container using 2.5 tons load. The canister was plugged with a stainless steel end plug which had a threaded hole in it. The assembly was soaked in a vacuum furnace for 2 hrs at 1650°F then cooled with nitrogen. The container was capped immediately upon removal from the furnace. The sample was then explosively compacted under water as before.

Sintering: The part was sintered at 2050°F for 1/2 hour in a vacuum.

Post Sintering Carbon Content: .16%

Heat Treatment: Austenitize 1650°F one hour; oil quench; temper 200°F (vacuum) 2 hours.

Surface Hardness: After the sample was quenched and tempered, the hardness ranged from R_b 88 to R_b 95.

Impact Strength: Three charpy V notch impact samples were made from the compact. The impact strengths were 10 ft-lbs, 8 ft-lbs, and 10 ft-lbs at room temperature. These were considered to be brittle failures.

Density: 96.4% of theoretical

Comments: The low impact strengths were attributed to the presence of oxides in the compact grain boundaries.

Shot No.: 5

Powder Container: 304 stainless steel seamless tubing 1.934 in. I.D. x .037 wall with stainless steel end plugs pressed into each end.

Metal Powder: 1565 grams Hoeganaes Ancorsteel 4600 plus .3% by weight No. 1615 graphite.

Explosive Charge: 1450 grams Thiokol No. 1005 sheet explosive initiated with a disk of Detasheet.

Compaction Technique: The powdered steel graphite was pressed into the container using 5 tons load. The canister was plugged with a stainless steel end plug which had a threaded hole in it. The assembly was soaked in a vacuum furnace for 2 hrs at 1650°F then cooled with nitrogen. The container was capped immediately upon removal from the furnace. The sample was then explosively compacted under water as before.

Sintering: The compact was sintered at 2200°F for 2 hours in a vacuum.

Post Sintering Carbon Content: .20%

Density: 97.23% of theoretical.

Comments: The compact had a center "spike" due to excessive explosive pressure. This is considered to be the result of changing from .050" wall to .037" wall tubing. Also, Thiokol 1005 explosive was used instead of 1004. The 1005 has a faster detonation velocity (by 1000 meter/sec) and approximately three times the detonation pressure. As a result, the shock produced by the detonation is more disruptive than that of the 1004 explosive.

Due to the condition of the sample, no further tests were made.

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In addition to the above study, a shelter was built for a 16 inch gun barrel breech section converted to a dual mode (vacuum chamber and isostatic press) pressure chamber system. The system was installed and testing in the vacuum mode was started. Part of the breech plug assembly failed during the tests and a replacement part was not received until after the project funds expired. After the failure of the breech plug, the chamber was converted to the isostatic press mode. The chamber will be used in this mode for compacting powdered metal using the wet bag process.

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